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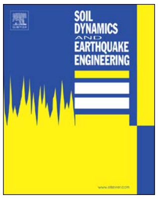

Evaluation of dynamic properties of sandy soil at high cyclic strains

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ABSTRACT

Dynamic loading conditions, such as earthquakes, may result in the generation of high shear strain ($> 5\%$) in the soil. Conventionally, dynamic properties of soils are estimated from the tests conducted up to a shear strain of 1% by considering Symmetrical Hysteresis Loop (SHL). However, it is commonly observed that the hysteresis loops become progressively asymmetric with increasing shear strain, which leads to the over- or under-estimation of the conventionally evaluated dynamic properties. Hence, it is necessary to adopt a modified methodology of evaluating the dynamic properties of saturated sands based on the actual Asymmetrical Hysteresis Loop (ASHL). Strain-controlled cyclic triaxial tests have been conducted, for a peak shear strain range of 0.015–4.5% at 1 Hz loading frequency, on test specimens prepared at different relative density (30–90%) and confining stress (50–150 kPa). Although, the shear modulus evaluated considering SHL and ASHL are on close agreement, the damping ratio evaluated considering SHL is approximately 40–70% lesser than that obtained by considering ASHL. Moreover, in contrast to the classical curves as largely applied in geotechnical engineering, a noticeable decrement of the damping ratio is observed beyond 0.75% shear strain.

1. Introduction

Past earthquake events have indicated that soils may experience peak shear strain levels greater than 5% [1–3]. The evaluation of the dynamic characteristics (*shear modulus* and *damping ratio*) of soils at such high strain levels is very essential for design of earthquake resistant structures. *Shear modulus* (or, more precisely, secant shear modulus) represents the stiffness of soil, whereas *damping ratio* is described as the percentage of energy loss per cycle of vibration. These dynamic properties are significantly affected by several factors, namely shear strain amplitude (γ), type and composition of soil, relative density (D_r), plasticity index, effective confining pressure (σ'_c), overconsolidation ratio (OCR), frequency of loading cycle (f), and number of cycles (N); the details of which are presented in [4–9] and are not repeated for the sake of brevity.

Several researchers have used different testing methodologies (e.g. resonant column test, piezoelectric bender element test, cyclic triaxial test and cyclic simple shear test) to determine the dynamic properties of different soils at varying strain levels [7,10–21]. It was reported that the response of soils at high strain levels ($> 0.01\%$) is substantially different than that at low strain levels ($< 0.001\%$), primarily due to the nonlinear stress-strain behaviour and damping characteristics at higher strains [6]. In contrary to most of the tests conducted for low-strain levels [10–21], only limited studies portrayed about the behaviour of soils under higher strains [2,22,23]. This paper presents the dynamic behaviour of sandy soil under high cyclic strains. Brahmaputra river sand was chosen for the purpose, and strain-controlled Cyclic Triaxial (CT) tests were performed at 1 Hz loading frequency for a peak shear strain range of 0.015–4.5%, on the reconstituted specimens prepared at different D_r (30–90%) and consolidated under different σ'_c (50–150 kPa). Although the cyclic tests can be conducted at various loading frequencies, 1 Hz loading frequency was chosen as recommended by Ishihara [6], Kramer [8] and commonly adopted by several other researchers [16,19–21]. The results obtained were analysed to assess the influence of high shear strain (γ), effective confining pressure (σ'_c) and relative density (D_r) on the evaluated dynamic properties.

2. Material characteristics

Brahmaputra sand (BS) obtained from Guwahati region (Assam, India) has been used for the study. The FESEM (Field Emission Scanning Electron Microscope) image of BS (Fig. 1) exhibits the particles to be profoundly angular and possessing noticeable surficial roughness. Particle size distribution of BS (Fig. 2), determined by conducting dry sieve analysis [24], classifies the soil to be poorly graded as per the relevant standards [25,26]. It can be observed that the soil belongs to the category of severely liquefiable soils zone [27]. Index properties of the soil (specific gravity, minimum and maximum dry unit weight) were determined as per relevant standards [28,29] and are presented in Table 1.

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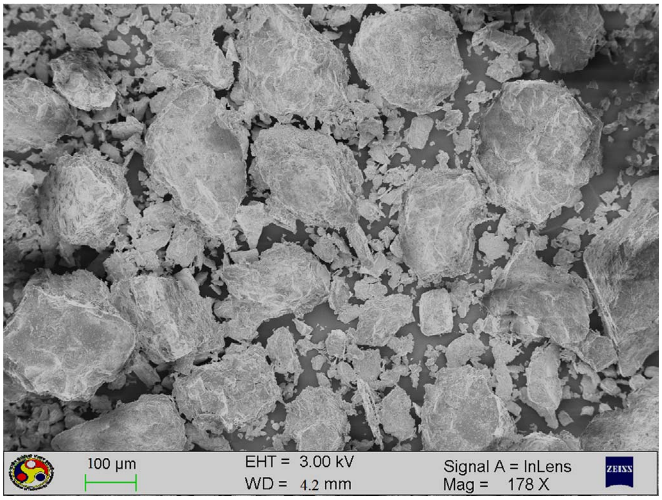

Fig. 1. FESEM image of Brahmaputra Sand (BS).

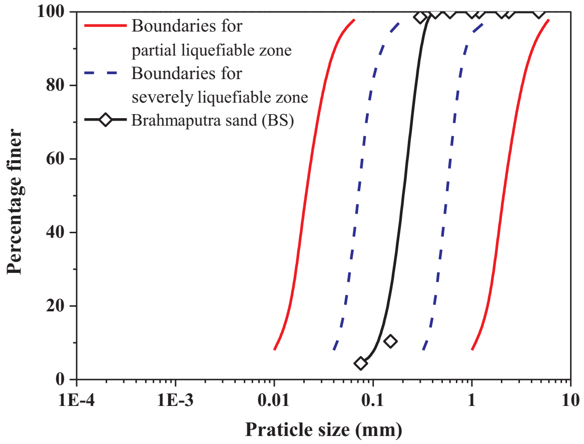

Fig. 2. Particle size distribution of BS.

Table 1
Physical properties of collected Brahmaputra sand.

Unit weight (kN/m^3)		Specific gravity	D_{10}	Uniformity coefficient	Coefficient of curvature
γ_{max}	γ_{min}		(mm)	C_u	C_c
16.84	13.85	2.7	0.13	1.47	1.09

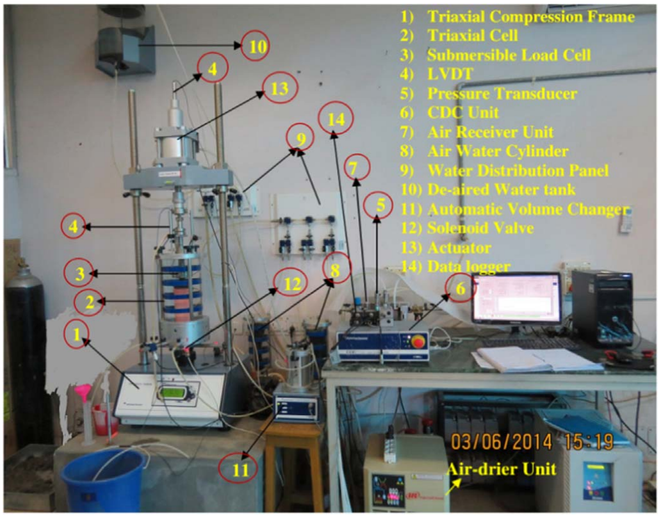

Fig. 3. Cyclic triaxial setup and components.

Table 2
Testing program for monotonic triaxial tests.

Sand specimen	Relative density D_r (%)	Confining pressure σ'_c (kPa)	Displacement rate (mm/min)
BS	30	50, 100, 150	1.2
	60	50, 100, 150	
	90	50, 100, 150	

3. Test apparatus and testing programme

The experimental investigations were conducted using an automated pneumatic controlled CT testing apparatus (Fig. 3). The apparatus consists of a 100 kN capacity loading frame fitted with a pneumatic dynamic actuator having a double amplitude displacement of 30 mm (± 15 mm) and operational frequency range of 0.01–10 Hz. The system comprises of a triaxial cell having a maximum confining capacity of 2000 kPa, and an air compressor with a maximum capacity of 800 kPa. The instrumentations available with the apparatus are: two linear variable differential transducers, one each for cyclic and static measurements, having a measuring range of ± 15 mm and up to 50 mm respectively; one submersible load cell of capacity 25 kN; three pressure transducers of capacity 1000 kPa to measure cell pressure, back pressure and pore-water pressure; and, one automatic volume change measuring device. The testing was controlled by a compact dynamic controller unit, which conveys the instructions provided by the DYNATRIAX software and also records the data with the help of a data logger.

All the tests were conducted on the remoulded cylindrical soil specimens of dimensions 70 mm diameter and 140 mm height [30]. Different specimen preparation techniques were reported in literature, namely dry pluviation, moist tamping and water sedimentation [30,31]. For the present investigation, dry pluviation technique was adopted. Each of the specimens were prepared in three layers. Dry sand was poured through a cone shaped funnel into the specimen-forming mould. A vacuum pressure of 15–20 kPa was applied before removing the mould to maintain the verticality of the specimen. Subsequently, the triaxial cell was mounted on the base plate and then filled with water, followed by simultaneous application of cell pressure (15–20 kPa) and release of vacuum pressure [31].

The specimen preparation was followed by subsequent saturation and consolidation stages. In order to expedite the saturation process, the specimen was flushed with CO_2 for 10–15 min at a pressure lower than 15–20 kPa, the initial cell pressure [31]. Subsequently, de-aired water was passed through the CO_2 flushed specimen. To attain the saturation, the cell pressure (CP) and back pressure (BP) were then gradually increased in stages while maintaining an almost constant differential pressure of 10 kPa. After each increment of CP, the Skempton pore-pressure parameter (B) was estimated to check the saturation status. The specimen was considered to be completely saturated when the B-value was obtained to be greater than 0.95. After attaining the saturation, the specimen was isotropically consolidated to